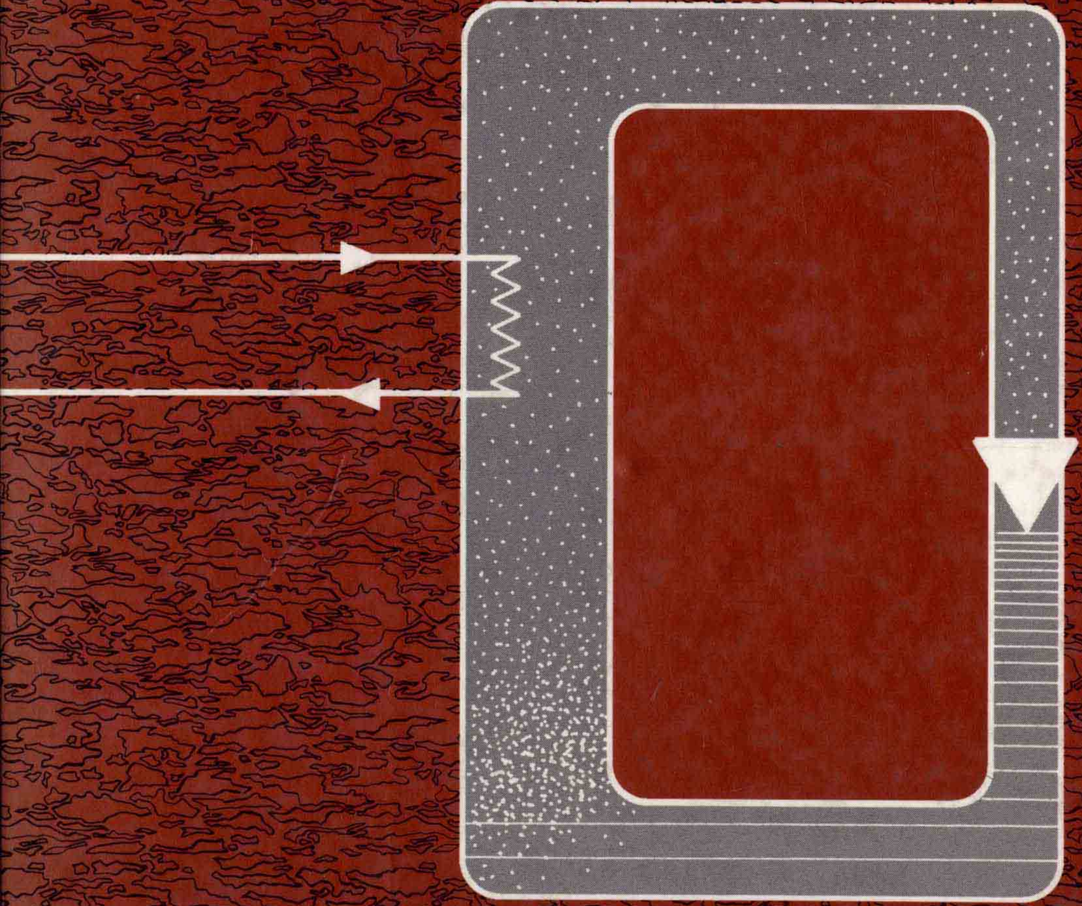
Prabir Basu
Scott A. Fraser

# Circulating Fluidized Bed Boilers

## DESIGN AND OPERATIONS



# CIRCULATING FLUIDIZED BED BOILERS

## DESIGN AND OPERATIONS

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# CIRCULATING FLUIDIZED BED BOILERS

## DESIGN AND OPERATIONS

*... dedicated to Rama Basu,*
*who inspired the work,*
*and paid dearly for it ....*

# PREFACE

This monogram is designed to provide practicing engineers and students with insight into the design and operation of circulating fluidized bed boilers. Prior exposure to the process of gas-solid fluidization may be an advantage, but it is not essential for full comprehension of this book. The book can provide engineers involved in steam generation or in the manufacture of circulating fluidized bed boilers an appreciation of the process, its capabilities, and its limitations. Experienced fluidization researchers are able to see how the principles of this phenomenon are applied to the design of circulating fluidized bed boilers.

The book is comprised of 10 chapters and 4 appendices, including 8 tables that are useful for design of circulating fluidized bed boilers and other fluidized bed equipment. The first chapter introduces readers to circulating fluidized bed boilers and compares this technology with others. Chapters 2 to 5 cover the basics of hydrodynamics, heat transfer, combustion, and gaseous emission, with special emphasis on their application in circulating fluidized bed boilers. Chapter 6 pulls together information in other chapters to a common approach to the design of this type of boiler. The relevance of design and feed-stock parameters to the operation of a circulating fluidized bed boiler is also discussed in this chapter. Designs of mechanical components, including cyclones, air distributor grids, and solid recycle systems, are discussed in Chapters 7 and 8. Disposal of solid wastes is a major facet of the operation of a circulating fluidized bed power plant and is discussed in Chapter 9. Circulating fluidized bed boilers present some special problems with construction materials, which are presented in Chapter 10 on material issues. Appendix I discusses physical characteristics of solids relevant to fluidization. The stoichiometric calculations needed for the heat and mass balance of the combustion reaction are presented in Appendix II. Tables IV.1-IV.8 present data calculated by the authors and those taken from other sources to aid in the conceptual design of circulating fluidized bed boilers. The circulating fluidized bed boiler is still an emerging technology. At the time of this writing, operating experience with these boilers is limited and somewhat inconsistent due to the variety of designs. As a result, some important practical aspects such as reliability and maintenance, have not been covered.

The need for this book was identified when the authors were evaluating designs for the 165 MWe circulating fluidized bed boiler at Point Aconi, Nova Scotia, Canada. Information needed for the design, evaluation, or analysis of the performance of circulating fluidized bed boilers were found scattered in many research papers and textbooks in related fields. Thus, efforts were made to collect and organize them into a coherent design sequence. Material in this book was first presented in several short courses on the design of circulating fluidized bed boilers held in Europe, Asia, and North America. The draft of this manuscript was also used as a textbook in two courses, Fluidization I and II, at the Technical University of Nova Scotia. The graduate students in mechanical and chemical engineering taking these courses and the industry participants at the short courses greatly contributed to shaping this book. Colleagues at several circulating fluidized bed boiler manufacturers, Nova Scotia Power Corporation, and at the Technical University of Nova Scotia helped with many useful suggestions and unpublished information. Drs. G. D. M. Mackay, J. H. Greenblatt, P. K. Nag, and Mr. D. G. Brown spent many hours editing the text. Mr. Song Wu, Chi Yong, Dr. A. Dutta, and Dr. J.L. Harness helped revise the manuscript. Mr. Wu also allowed us use portions of his Ph.D work at the Technical University of Nova Scotia. The nimble fingers of Mrs. Zhuan Zheng and Rita Gyrmati typed as many as six versions of this manuscript. The authors are grateful to the publishers and authors who permitted free use of their materials in this book. Final thanks go to Atreyee and Atreya Basu for their active help in the preparation of the manuscript and provided their support for this project.

Prabir Basu
Scott Fraser

# CONTENTS

# CHAPTER 1

# INTRODUCTION

On December 16, 1921 in Germany, Fritz Winkler introduced gaseous products of combustion into the bottom of a crucible containing coke particles; the event marked the beginning of a very important chapter of modern technology. Winkler saw particles lifted by the drag of the gas and the mass of particles looked like a boiling liquid (Squires, 1983). This little experiment initiated a new process called *Fluidization*.

Though some would argue that the phenomenon of the *fluidized bed* (Section 2.1) was observed by many others in the past, the credit for the invention of the *bubbling fluidized bed* process (Section 2.1.1), which we use for scores of processes— including combustion— today, should go to Winkler. He not only observed the process, but also took measurements, filed a patent, and built commercial fluidized bed plants as large as 12 $m^2$ in cross section — very large even by today's standards.

The idea of burning coal in a bubbling fluidized bed may have crossed the minds of many innovators and scientists, but it was pursued and promoted most vigorously by Douglas Elliott. In the early 1960s, he recognized the merit of burning coal in fluidized beds to generate steam by immersing boiler surfaces in the bed. He advocated the use of fluidized bed for steam generation with the British Coal Utilization Research Association and the National Coal Board of the UK. An active program for the development of fluidized bed combustion started shortly after Elliott's exploratory work at the Central Electricity Generation Laboratory at Marchwood.

Simultaneous development in bubbling fluidized bed boilers continued in the USA and China, but the lack of a recorded history of the development of the fluidized bed boiler in those two countries does not permit those developments to be included here. However, many types of the bubbling fluidized bed boiler have been developed and commercialized since the early work in the UK, USA, and China.

The *circulating fluidized bed* (CFB) boiler (Section 1.1), the next generation of fluidized boilers (Figure 1.1), had a curious beginning. Warren Lewis and Edwin Gilliland conceived a new gas-solid process at the Massachusetts Institute of Technology in 1938 when they were trying to find an appropriate gas-solid contacting process for fluid catalytic cracking. It is interesting that they invented the *fast fluidized bed* process (Section 2.2) while unaware of the invention of the other form of essentially the same fluidized bed process invented by Winkler at least 17 years earlier (Squires, 1986).

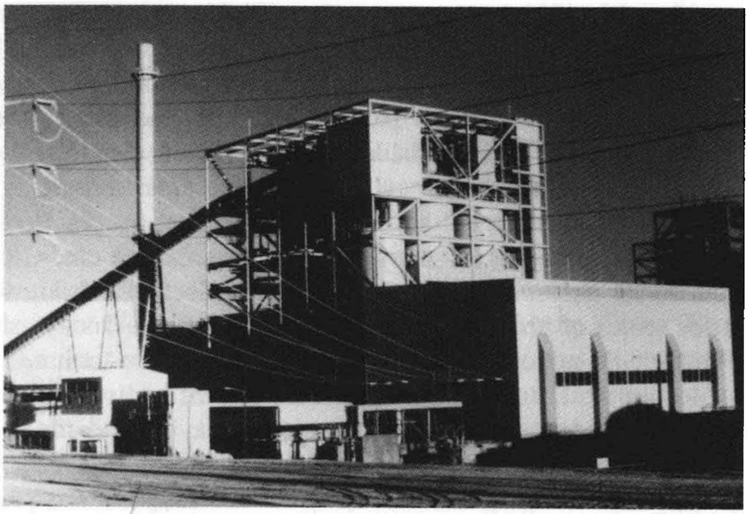

Figure 1.1 Photograph of a CFB boiler plant. [Reprinted with permission of the Pyropower Corporation.]

Though the circulating fluidized bed process was used extensively in the petrochemical industries, it did not have a direct entry into the field of coal combustion for steam generation. A number of groups worked independently. Among them were Lurgi, who found in fast fluidization an excellent technique for carrying out operations with fine solids at very high velocity. Based on laboratory-scale work in their Metallgesellschaft laboratories, Lurgi developed an aluminum calcining process, which was tested in a 24 ton-per-day pilot plant at Vereinigte Aluminum Werke AG, Luenen during the 1960s. It was followed by a commercial plant of 500 tons per day in 1970 at Luenen.

recovered in a multistage fluidized bed cooler, where waste gases exchanged heat with feed materials. Use of the circulating fluidized bed process allowed the uniform control of the calcining temperature within required limits. As a result of this attractive feature a large number of CFB calciners were soon put into commercial operation (Reh, 1986). The precalcining stage of the cement clinkering process is a highly exothermic process. Lafrage, Creusot Loire Enterprises, and Lurgi used a circulating fluidized bed precalciner to provide heat by burning high ash coal or shale (Figure 1.2). This demonstrated the use of CFB combustion for low-grade coal (Kuhle, 1984). The first CFB bed boiler, designed exclusively for the supply of steam and heat, was built in the Vereinigte Aluminum Werke at Luenen in 1982. This plant generated 84 MW total (9 MW electricity, 31 MW process steam, 44 MW molten salt melt) by burning low grade coal washing residues in the presence of limestone to meet the German emission legislation. Thus, at Lurgi the application of the circulating fluidized bed technique to coal combustion for steam generation followed a natural evolutionary process.

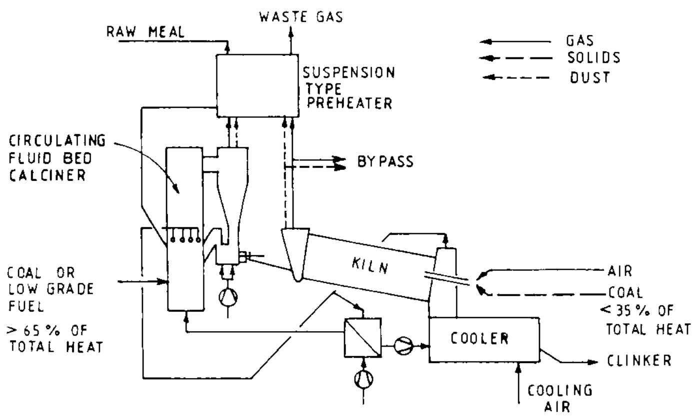


Figure 1.2 Circulating Fluidized Bed Pre calciner for making cement [Reprinted with permission from Reh, L. (1986). Circulating Fluidized Bed Technology, P.Basu, ed., Pergamon Press Plc.]

The Ahlstrom group in Finland, on the other hand, started out with the development of bubbling fluidized bed boilers in the late 1960s. In an effort to improve the performance of their bubbling fluidized bed sludge incinerator, Ahlstrom experimented with recycling fine ores using a hot cyclone while operating the bed at a velocity of 3 m/s. In spite of heavy entrainment of the particles, an overall improvement in the combustion of fuel particles was observed.

Following a series of experiments in their Hans Ahlstrom Laboratory, they built the first commercial CFB boiler at Pihlava, Finland. It was a 15 MWt (thermal output) boiler retrofit to an existing oil-fired boiler. This boiler replaced expensive oil with peat. Initially the circulating fluidized bed boilers built by Ahlstrom were primarily for multi-fuel or low grade fuels, such as bark, peat, wood waste, etc. Later boilers were designed exclusively for burning coal. One major difference in these designs (Figure 1.3) from that developed by Lurgi (Figure 3.1) was that Ahlstrom units did not use the external heat exchanger used by Lurgi boilers. The required heat was absorbed entirely by the furnace surfaces.

The other group engaged in the early development of circulating fluidized bed boilers was Battelle Memorial Laboratory in the USA. In Battelle's combustor, fuel and, if necessary, limestone are fed into a bed of inert, closely sized coarse particles maintained in turbulent fluidization at high gas velocities. The entrained solid (fly ash, unburned carbon, unreacted and spent limestone) is circulated via a hot cyclone and an external heat exchanger. The first commercial unit was a 23 tons/hr. steam boiler commissioned in 1981. Unlike Lurgi or Ahlstrom, Battelle used a very high gas velocity in the combustor and called it *Multi Solid Boiler.*

## 1-1 WHAT IS A CIRCULATING FLUIDIZED BED BOILER ?

*A circulating fluidized bed (CFB) boiler is a device for generating steam by burning fossil fuels in a furnace operated under a special hydrodynamic condition: where fine solids (Geldart Group A or B[1]) are transported through the furnace at a velocity exceeding the terminal velocity of average particles, yet there is a degree of refluxing of solids adequate to ensure uniformity of temperature in the furnace.*

The major fraction of solids leaving the furnace is captured by a gas-solid separator and is recirculated back to a point near the base of the furnace at a rate sufficiently high to cause a minimum degree of refluxing of solids in the furnace. A CFB boiler is shown schematically in Figure 1.3. The primary combustion air (usually sub-stoichiometric in amount) is injected through the floor grate of the furnace, and the secondary air is injected from the sides at a certain height above the furnace floor. Fuel particles burn in the furnace, generating heat. A fraction of the combustion heat is absorbed by water/steam cooled surfaces located in the

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1. Geldart's particle groups are explained in Appendix .I

furnace and the rest is absorbed in the convective section located further downstreams known as the *back-pass*.

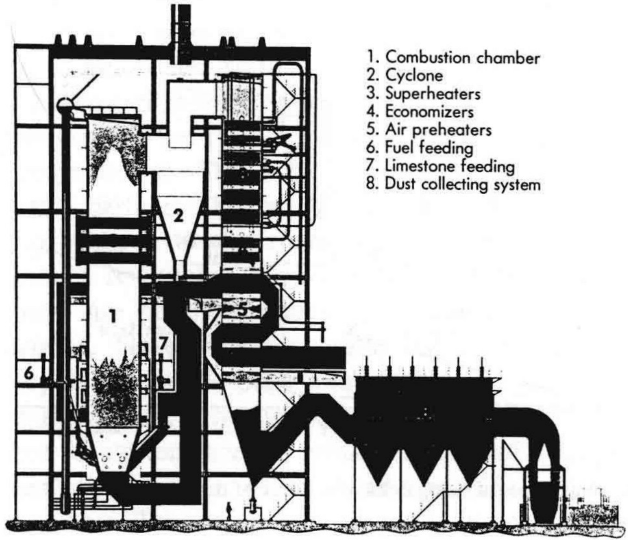


Figure 1.3 Schematic diagram of a CFB boiler.

The creation of the special hydrodynamic condition, popularly known as *fast Bed* or *dilute phase refluxing*, is key to the circulating fluidized bed process. A special combination of gas velocity, recirculation rate, solids characteristics, volume of solids, and the geometry of the system gives rise to this special hydrodynamic condition under which solid particles are fluidized at a velocity greater than the *terminal velocity* (Appendix I.1) of individual particles. Yet these particles are not entrained immediately as expected in vertical pneumatic transport systems. On the contrary, solids are found to move up and down in the form of aggregates, causing a high degree of refluxing. These long slender solid agglomerates move vertically, sideways, and downwards. They are continuously formed, dispersed, and reformed again. This special transport process is also capable of carrying a limited number of large particles, whose terminal velocity is much higher than the average velocity through the furnace. This motion of gas and solids gives rise to a high level of slip velocity between them. This characteristic, compared in Figure 1.4 and Table 1.1, sets it apart from other types of boilers.

## 1-2 FEATURES OF A CIRCULATING FLUIDIZED BED BOILER

The furnace of a CFB boiler contains a mass of granular solids, generally in the size range of 0.1-0.3 mm. It includes

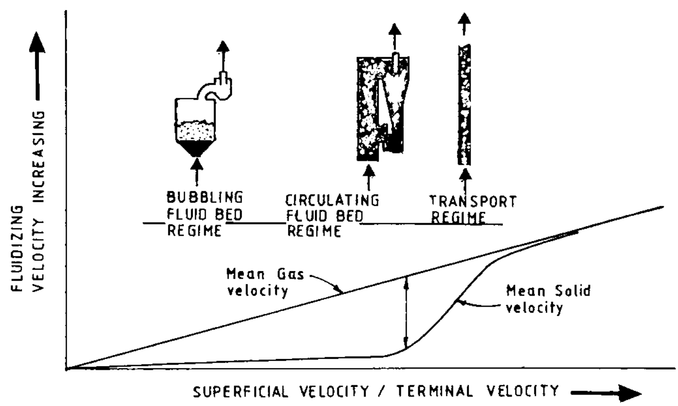


Figure 1.4 A comparison of design characteristics of different types of firing for boilers.

1. Sand or gravel (low ash fuels, such as wood-chips)
2. Fresh or spent limestone (boilers burning high-sulfur coal and requiring control of sulfur emission)
3. Ash from coal (boilers firing high or medium ash coal requiring no sulfur retention)

Sometimes a combination of bed materials is also used. The size of fuel particles, especially for the low-ash variety, do not necessarily have a major bearing on that of bed materials, because they constitute only a minor fraction ( 1-3%) of the total bed materials in the CFB furnace.

### 1-2-1 Description of the Boiler

The boiler can be divided into two sections. The first section comprises :

1. Furnace or fast fluidized bed
2. Gas-solid separator (cyclone or impact separator)
3. Solid recycle device (loop seal, seal pot, or L-valve)
4. External heat exchanger (optional)

These components form a solid circulation loop in which fuel is burned. The furnace enclosure of a CFB boiler is generally made of water tubes as in pulverized coal-fired (PC) boilers. A fraction of the generated heat is absorbed by these heat-transferring tubes. The second section is the back-pass, where the remaining heat from the flue gas is absorbed by the reheater, superheater, economizer, and air-preheater surfaces. Additional but less crucial components attached to a CFB boiler are the bed drain and the solid classifier

The lower part of the first section (furnace) is smaller and is often tapered in cross section. This helps to maintain good fluidization, even with segregated particles. The walls of the lower section are lined with refractory up to the level of secondary air entry or above. Beyond this level the furnace is uniform in cross section and larger than the lower part. Its walls are generally cooled by evaporative, superheater, or reheater surfaces. The gas-solid separator and the non-mechanical valve for solid recycle are located outside the furnace (Figure.1.3). These are also lined with refractory. In some designs a part of the hot solids recycling between the cyclone and the furnace is diverted through an external heat exchanger (Figure 3.1), which absorbs an additional fraction of the combustion of heat. This heat exchanger is a bubbling fluidized bed with heat transfer surfaces immersed in it. Very little combustion takes place in the external heat exchanger.

Coal is generally injected into the lower section of the furnace. It is sometimes fed into the loop-seal, from which it enters the furnace along with returned hot solids. Limestone is fed into the bed in a similar manner. Coal burns when mixed with hot bed solids.

The primary combustion air enters the furnace through an air distributor or grate at the furnace floor. The secondary air is injected at some height above the grate to complete the combustion. Bed solids are well mixed throughout the height of the furnace. Thus, the bed temperature is nearly uniform in the range of 800-900°C, though heat is extracted along its height. Relatively coarse particles of sorbent and unburned char are captured in the gas-solid separator and are recycled back near the base of the furnace. Finer solid residues (ash and spent sorbents) generated during combustion and desulfurization leave the furnace, escaping through the gas-solid separators, but they are collected by a bag-house or electrostatic precipitator located further downstream.

### 1-2-2 Advantages of Circulating Fluidized Bed Boilers

Circulating fluidized bed boilers have a number of unique features that make them more attractive than other solid fuel fired boilers. These features include (Yerushalmi, 1986) the followings:

*Fuel Flexibility*

This is one of the major attractive features of CFB boilers. Fuel particles constitute less than 1-3% by weight of all bed-solids in the furnace of a typical CFB boiler. The rest of the solids are noncombustibles: sorbents, fuel-ash or sand. The special hydrodynamic condition in the CFB furnace allows an excellent gas-solid and solid-solid mixing. Thus fuel particles fed to the furnace are quickly dispersed into the large mass of bed-solids, which rapidly heat the fuel particles above their ignition temperature without any significant drop in the temperature of the bed solids. This feature of a CFB furnace would ideally allow it to burn any fuel without the support of an auxiliary fuel, provided its heating value is sufficient to raise the combustion air and the fuel itself above its ignition temperature. Thus, a wide range of fuels can be burned in one specific boiler without any major change in the hardware. Many commercial CFB boilers run on 40-60% ash coal.

To maintain the combustion temperature within an optimum range, it is necessary to absorb a certain portion of the generated heat from the combustion zone. This fraction varies from one fuel to an other. A CFB accomplishes this for different types of fuels by controlling the amount of heat absorbed in the furnace by adjusting the heat extraction from the recirculating solids outside the furnace by means of an external heat exchanger. In boilers without the external heat exchanger, the hydrodynamic condition of the furnace can be adjusted such as to change the solids concentration in the furnace; this, in turn, alters the heat absorbed by the furnace.

*High Combustion Efficiency*

The combustion efficiency of a CFB boiler is higher than that of bubbling fluidized bed boilers. It is generally in the range of 99.5 to 97.5%. The following features contribute to the high combustion efficiency of circulating fluidized bed combustors.

- Better gas-solid mixing
- Higher burning rate (especially for coarser particles)
- A majority of unburned fuel particles are recycled back to the furnace